Naval Surface Warfare Center
Carderock Division
West Bethesda, MD 20817-5700

NSWCCD-83-TM-2013/36 September 2013

Carderock DTIC Catalogue # 80-TR-2014/015

Naval Architecture and Engineering Department

Technical Report

EMPIRICAL EQUATIONS FOR DEVELOPING RIDE SEVERITY ENVELOPES FOR PLANING CRAFT LESS THAN 55 FEET IN LENGTH

By

Combatant Craft Division, Code 83

NAVSEA
WARFARE CENTERS
Carderock

NSWCCD-83-TM-2013/36 Empirical Equations for Developing Ride Severity Envelopes for Planing Craft Less Than 55 Feet in Length

EMPIRICAL EQUATIONS FOR DEVELOPING RIDE SEVERITY ENVELOPES FOR PLANING CRAFT LESS THAN 55 FEET IN LENGTH

NSWCCD-83-TM-2013/36

Prepared by:

Michael R. Riley
Senior Data Analyst
The Columbia Group

Prepared by:

Jason Marshall
Senior Craft Design Manager,
Naval Architecture Branch
NSWCD Code 831

Reviewed by:

Kelly Haupt
Senior Test Engineer
Test and Evaluation Branch
NSWCCD Code 835

Reviewed by:

Don Jacobson
Naval Architect
Naval Architecture Branch
NSWCCD Code 831

Approved by:

David Pogorzelski
Branch Head
Test and Evaluation Branch
NSWCCD Code 835

Approved by:

Willard Sokol III
Branch Head
Naval Architecture Branch
NSWCCD Code 831

Post-Release Revisions

Revision	Reviewer/ Approver	Date	Change Description	Page, Section

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
20-09-2013

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
May 2013 to Sep 2013

4. TITLE AND SUBTITLE
Empirical Equations for Developing Ride Severity Envelopes for Planing Craft Less Than 55 Feet in Length

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Riley, Michael R., The Columbia Group
Jason T. Marshall, Code 831

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

NAVSEA Carderock
Naval Surface Warfare Center
Combatant Craft Division
2600 Tarawa Court, #303
Virginia Beach, Virginia 23459-3239

8. PERFORMING ORGANIZATION REPORT NUMBER
NSWCCD-80-TR-2014/015
NSWCCD-83-TM-2013/36

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
NAVSEA Carderock
Naval Surface Warfare Center
Combatant Craft Division
2600 Tarawa Court, #303
Virginia Beach, Virginia 23459-3239

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Distribution Statement A: Approved for public release. Distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This report presents empirical equations for estimating curves of constant $A_{1/100}$ and $A_{1/10}$ peak acceleration as a function of craft average speed and significant wave height for high-speed planing craft with nominal lengths less than 55 feet. When combined with safety, operational, structural, or propulsion system limit criteria, the equations are useful for creating operational envelopes or safe operating envelopes.

15. SUBJECT TERMS
Seakeeping Acceleration data Ride severity Operational envelopes SOE

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON: Jason Marshall
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
Unclassified	Unclassified	Unclassified	See 12.	32	757-462-3503

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

This page intentionally left blank

Contents

Page

Figures

Page

Tables

Page

Administrative Information

This work was performed by the Combatant Craft Division (Code 831) of the Naval Architecture and Engineering Department of Naval Surface Warfare Center, Carderock Division (NSWCCD).

Acknowledgements

The authors would like to thank many individuals for providing important information critical to the development of this report. Mr. Donald L. Blount, Donald L. Blount and Associates, Inc. shared historical information related to the development and use of Navy criteria for estimating crew comfort and effective mission performance levels. Mr. David Shepard, Project Officer, USCG Office of Boat Forces (CG-731) shared historical documents and described criteria and rationale for constructing and using operational envelopes. Ms. Dina Kowalyshyn, Principal Naval Architect, Band Lavis Division, CDI Marine Company shared craft acceleration criteria and classification society information.

From the NSWCCD Det Norfolk, Combatant Craft Division, numerous individuals provided comments and suggestions that improved the quality of the first draft of the report, including the Naval Architecture Branch, Code 831, Mr. Willard Sokol, Mr. Carl Casamassina, Mr. Richard Wilson, and Mr. Donald Jacobson; from the Test and Evaluation Branch, Code 835, Mr. David Pogorzelski, Mr. Kelly Haupt, Mrs. Heidi Murphy, Dr. Neil Ganey, and Mr. Tom Kush. Mr. Malcolm Whitford, CDI Marine, Inc., Senior Naval Architect also provided valuable feedback comments on the first draft of the report. Their collective knowledge and willingness to share is greatly appreciated.

This report is dedicated to Mr. Joseph G. Koelbel, Jr., Naval Architect, 29 October 1928 – 14 January 2013. His numerous papers on the subject, along with those of Donald L. Blount, David Fox, Stephen Denny, E. Nadine Hubble, and Daniel Savitsky provided foundational information for this report.

Summary

This report summarizes historical crew comfort and performance criteria and presents methods for developing speed versus wave height envelopes for high-speed planing craft. In the absence of craft specific data, empirical equations based on limited data for craft with nominal lengths less than 55 feet are presented for estimating acceleration values as a function of craft weight, average speed, and significant wave height. Predictions for speeds and wave heights outside the empirical range of applicability are extrapolations that should be confirmed by future data.

Introduction

Purpose

The purpose of this report is to summarize how the combination of crew comfort and performance criteria and equations for estimating average peak accelerations can be used to construct ride severity envelopes for planing craft. The envelopes provide a baseline for constructing safe operating envelopes for high-speed planing craft.

Scope

The equations for computing speed versus wave height envelopes presented in this report are applicable only to small planing craft that weigh in the range of 14,000 pounds to 38,000 pounds with lengths from 33 feet to 55 feet. The equations are based on acceleration data recorded in rough seas with short wave periods like those typically observed on the east coast of the United States on the order of 6.5 seconds or less. The equations are therefore not applicable for waves with longer periods (e.g., wave periods typically observed on the west coast of the United States on the order of 8-seconds or more). The wave height versus speed envelopes shown in the report were developed using historical crew comfort and mission performance criteria. Personnel injury modeling is beyond the scope of the report.

Background

When a small planing craft's speed increases in rough seas the severity of individual wave impacts also increases. The severity of a wave impact is often described in terms of peak vertical acceleration. Depending upon the size of the craft, increasing vertical impact accelerations can lead to numerous problems if craft speed is not reduced.

This report does not focus on how to develop safe operating envelopes, but discussion of the topic in this introduction explains how the empirical equations and ride quality criteria presented later in the report could be used with other craft specific limit criteria to construct safe operating envelopes.

The ability of a helmsman to maintain safe operations begins with training and experience. The training may or may not include guidance on safe combinations of craft speed and significant wave height as shown in Figure 1. The curves are notional and are meant to convey how different criteria establish limit lines for a specific craft. These types of curves, referred to collectively as safe operating envelope, operating envelope, or operational envelope, typically show curves where operations transition for a given payload from low risk to higher risk conditions as speed and wave height increase[1] [1, 2].

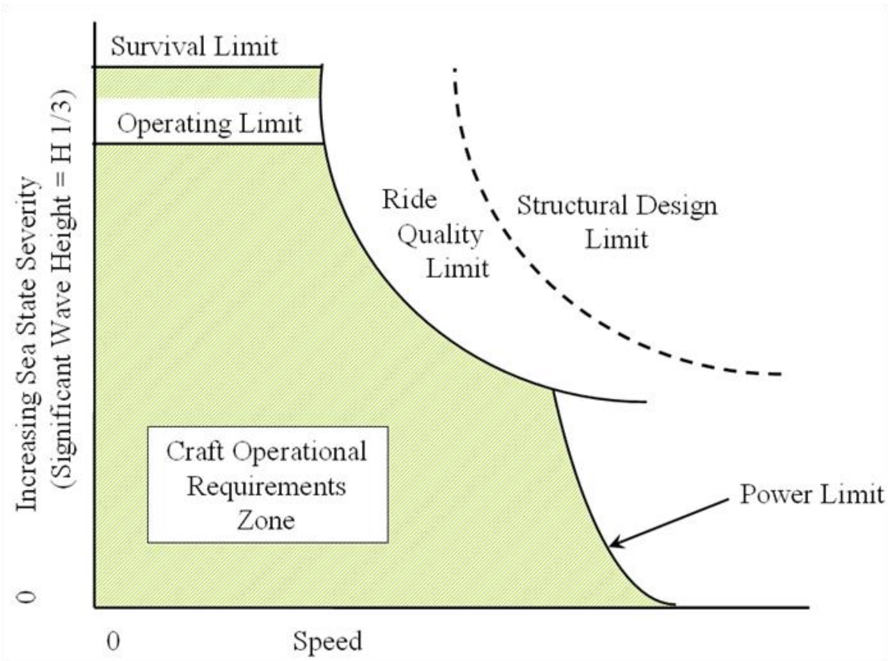

Figure 1. Example Operational Envelopes for Small Planing Craft

An operational envelope for high-speed planing craft can be constructed using many different types of criteria limits depending upon craft size and mission requirements. For example, the limit criteria can be related to power availability, crew safety, crew habitability (i.e., ride quality), structural integrity, or required sea-state survival limits[2] [3]. At low speeds the upper limit is typically established by the required maximum operating wave height and survival wave height. As wave height increases, the severity of wave impacts will typically limit craft speed because the coxswain will not want to increase speed due to concerns for craft stability or personnel comfort and performance. As shown in the figure this is often referred to as the ride quality limit[3 4].

The separation between the ride quality limit and the hull structural design limit typically depends upon the size (i.e., weight) of the craft as well as the mission of the craft. For example, on smaller craft the low craft weight results in large peak vertical accelerations that can have

---

[1] DTNSRDC-SDD-114-24, August 1976
[2] NAVSEADET Norfolk-6660-69, December 1980
[3] NAVSECNORDIV-6660-39, August 1978
[4] NAVSEA Combat Systems Engineering Station Norfolk Report 60-115, August 1983

negative effects on ride quality for personnel or on equipment operability that could be experienced well before a structural stress limit is reached. On very large craft (e.g., 60 tons or more) the weight of the craft may result in low peak vertical accelerations that are not troublesome for passengers, or crew, or onboard electronics equipment, but the large wave impact loads on the hull structure may lead to excessive structural stresses. These differences between smaller weight craft and larger weight craft illustrate how safe operating criteria or operating limits can vary from one craft design to another. Another type of limit is the power limit. This limit is where the maximum speed is achieved for a given wave height based on the craft's installed propulsion system.

The lines that define the ride quality limits for small planing craft are typically based on predictions of peak vertical acceleration as a function of craft average speed and significant wave height. In actual practice the lines are not hard limits, but are rather meant to show a best estimate of where a transition would occur. For example, recent analyses of full-scale planing craft data indicate that for a given average craft speed (that may vary +/- 3 knots during a trial), the significant wave height at which an average peak acceleration is observed may vary +/- 6-inches [5]. When this information is combined with the concept that different people have different perceptions of comfort and discomfort, it becomes clear why the ride quality envelopes are best described as transition zones for a specific craft.

Operational envelopes are not required or not appropriate for all craft. The interest in developing one typically depends upon the intended operational scenarios of a craft. For example, at one end of the spectrum, the passenger ferry that delivers tourists to view the Arizona Memorial in Pearl Harbor, Hawaii operates in calm waters at very low speeds, so operating envelopes for this type of displacement hull would not be needed. At the other end of the spectrum are planing craft operations at high-speeds in rough seas. In these conditions the knowledge and skill of an experienced helmsman is very important [1], and operation within the operating envelope provides the lowest manageable level of risk.

If operational envelopes are of interest, they can be constructed by combining safe limit criteria at very low speeds with other criteria, including ride quality limits, structural limits, and powering limits at higher speeds. This report focuses only on suggested procedures for computing ride severity envelopes that are curves of constant peak acceleration. Historical ride quality criteria based on crew comfort and performance are introduced in the following paragraphs to illustrate the computational process. Other limit criteria used to develop safe operating envelopes are craft and mission specific, and are beyond the scope of this report.

Wave Impact Severity

Several key parameters can be used to describe what is typically perceived as unpleasant or uncomfortable experiences (i.e., rides) in planing craft. Fore-aft rigid body decelerations can cause individuals to lurch forward much like the hard application of brakes in an automobile, and pitch, pitch rate, roll, and roll rate can lead to uncomfortable motions similar to whiplash, especially in the neck and spine regions. Motions in a transverse (e.g., port-starboard) direction must also be considered because of the different direction of deceleration forces (e.g., beam and quartering seas) when impacting a wave. All of these distinguishing attributes of a ride determine the overall quality or roughness of the ride. When impact accelerations and rates of rotation are

[5] NSWCCD-23-TM-2012/38, October 2012

low, the comfort level will typically be perceived as higher (neglecting motion sickness) and the crew will more likely be able to perform their functions without decreased proficiency over time. Good human performance attributes such as these are part of the overall description of a hull design that has good seakeeping qualities [4].

The most common parameter used to describe ride severity has been the vertical rigid body acceleration [1 to 8]. Vertical accelerations tend to be a better discriminator because they vary over a larger range than other parameters like pitch or roll. As accelerations increase with speed and wave height, the discomfort experienced can rapidly lead to extreme discomfort for seated personnel [9, 10]. As summarized in Appendix A, rigid body heave accelerations should be used to quantify wave impact loads on hull structure, equipment, and personnel. Acceleration values are typically based on the same zero reference where -1 g is the acceleration due to gravity. The fundamental unit of acceleration is length per time-squared (e.g., ft/sec^2), but values given in most publications are normalized for convenience by dividing by the acceleration due to gravity (e.g., 32.2 ft/sec^2).

The widespread practice of averaging peak vertical accelerations over time was adopted to account for the variability of ocean waves with time. Recorded acceleration data is processed to calculate the average of the larger peak accelerations, including the average of the highest ten percent called the average of the one-tenth highest peaks ($A_{1/10}$), and the average of the highest one percent called the average of the one-one hundredth highest peaks ($A_{1/100}$).

In this report all accelerations are vertical rigid body accelerations (i.e., heave accelerations) decomposed from unfiltered acceleration data using a low-pass filter to remove acceleration components caused by structural vibrations in the vicinity of the gage. Appendix A explains why rigid body heave accelerations are directly related to the impulsive load of a wave impact.

StandardG

StandardG is a software package that applies a four-step process to recorded acceleration data to extract the accelerations associated with the rigid body motions of planing craft. Rigid body accelerations can then be used in reverse-engineering processes to estimate dynamic loads caused by wave impacts. The first two steps apply principles of response mode decomposition to determine rigid body content in the recorded acceleration signal. The second two steps were developed specifically for computing the unambiguous average of the highest $1/N^{th}$ peak accelerations used in naval architecture applications. The use of the *StanardG* four-step process enables comparisons of acceleration data results developed by independent researchers and among different organizations [8].

The *StandardG* algorithm for extracting rigid body peak accelerations from full-scale acceleration data and computing standardized $A_{1/N}$ values is available for evaluation from John Zseleczky, P.E., Branch Head, Hydromechanics Lab, U.S. Naval Academy, johnz@usna.edu, (410) 293-5102. It can be run by MATLAB™ or Octave™ software. The information package includes sample raw acceleration data, explanatory text files, computational results, and applicable papers and reports. The algorithm was specifically developed for computing rigid body $A_{1/N}$ accelerations using acceleration data acquired using accepted instrumentation practices [11].

Figure 2 shows an example unfiltered acceleration record for a planing hull in head seas. The plot shows hundreds of wave impacts during the 528-second run. The plot shown in Figure 3 shows output from the *StandardG* algorithm for the acceleration record shown in Figure 2. The filtered (10-Hz low-pass) peak accelerations for each of the 344 wave impacts larger than the RMS value are plotted largest to smallest. The RMS acceleration was 0.64 g. The largest peak acceleration (labeled in the figure as A_{max}) was 4.63 g, $A_{1/100}$ was 4.19 g, and $A_{1/10}$ was 2.75 g.

The results shown in Figure 3 are applicable to one craft at one specific average speed for one significant wave height. The next section summarizes data trends that show how the average peak acceleration amplitudes vary with craft weight, average speed, and significant wave height.

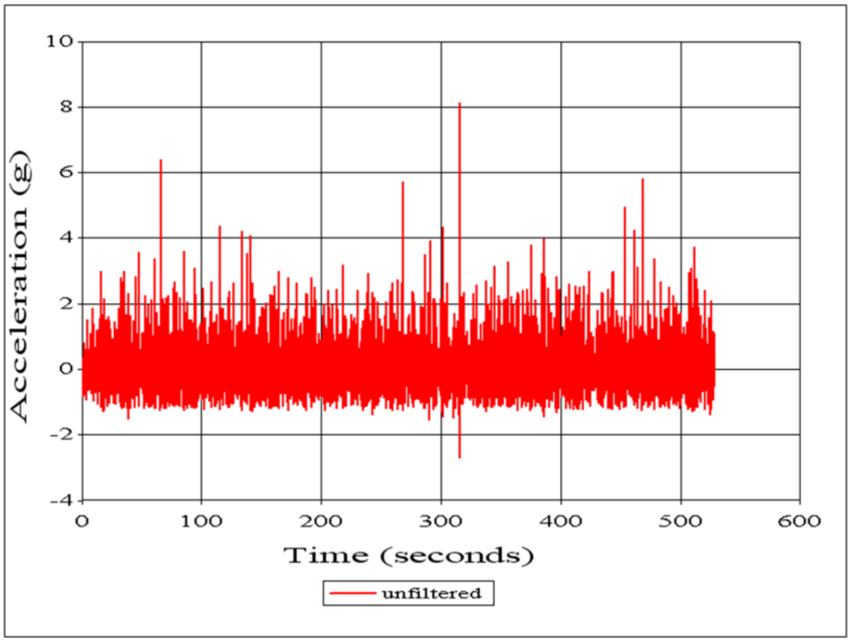

Figure 2. Example Unfiltered Acceleration Record

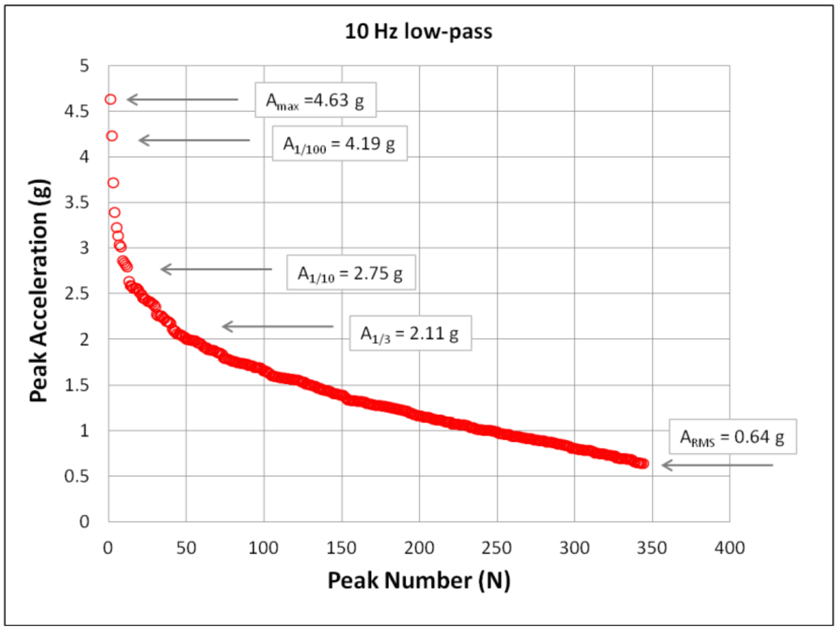

Figure 3. *StandardG* Algorithm Peak Acceleration Output

Peak Acceleration Equations

Acceleration Database

Analyses of acceleration data recorded during seakeeping trials for fifteen craft in head seas found that observable trends existed within two craft weight categories [6]. Category A includes craft that weigh from 14,000 pounds to 18,000 pounds. Category B includes craft that weigh from 22,000 pounds to 38,000 pounds. Table 1 lists characteristic parameters for craft in each weight category. The beam loading coefficient is the displacement of the craft divided by the product of the mass density of water and the craft beam cubed. Trim is static trim, and in the eighth column the speed ratio is craft speed (V) divided by the square-root of craft length (L, length overall).

[6] NSWCCD-23-TM-2012/38, October 2012

Table 1. Craft Characteristics

Craft Category	Craft Weight (lb)	Beam Loading Coefficient	L/B	Trim (deg)	Deadrise (deg)	$H^{1/3}$ / B	V / $L^{1/2}$	Volume Froude Number
A	14,000 to 18,000	0.28 to 0.46	3.9 to 4.2	3 to 5	18 to 21	0.22 to 0.45	1.2 to 6.1	2.5 to 5.2
B	22,000 to 38,000	0.18 to 0.60	3.0 to 4.2	3 to 5	18 to 22	0.16 to 0.60	1.5 to 5.9	1.8 to4.0

Accelerations recorded vertically at the longitudinal center of gravity (LCG) of each craft were run through the *StandardG* algorithm. Fourier spectra analyses indicated that a 10-Hz low-pass filter was appropriate for extracting the rigid body heave peak accelerations. Values of deadrise and trim for each sub-set of data did not vary sufficiently to characterize trends within the data.

Equations for Category A Craft

Category A included five deep-V planing-hull craft (deadrise from 18 to 21 degrees) with weights between 14,000 pounds and 18,000 pounds, lengths from 36 feet to 40 feet, and beams from 8.5 feet to 9.0 feet. Data from all seven available runs for these five craft followed the same trends for both $A_{1/100}$ and $A_{1/10}$ values for testing conditions that varied from roughly 21 knots to 45 knots and significant wave heights from approximately 1.9 feet to 4.8 feet. The trend equations estimate peak vertical accelerations (i.e., rigid body heave) in units of *g* at the LCG of the craft. V_s is craft average speed in knots, and H is significant wave height in feet. A_{peak} is the peak amplitude for a single wave impact. Because of the small number of craft in this data sub-set, the following equations should be used as an interim estimate until more data is available.

$$A_{1/100} = \frac{(V_S + 12.63)(H_{1/3} - 0.73) - 11.14}{21.72} \qquad \text{Equation (1)}$$

$$A_{1/10} = \frac{(V_S + 0.77)(H_{1/3} - 0.70) - 5.52}{25.6} \qquad \text{Equation (2)}$$

Values of $A_{1/100}$ (in units of g) are estimated within -0.28 g to +0.19 g (i.e., within -7.05% to +6.32%) for 2 g < $A_{1/100}$ < 6.1 g. Values of $A_{1/10}$ for Category A craft are estimated within -6.33% to 3.32% of the data. Figure 4 and Figure 5 shows example constant acceleration curves computed using equations (1) and (2). The gray rectangles in Figure 4 are ranges of uncertainty for $A_{1/100}$ values for three data points.

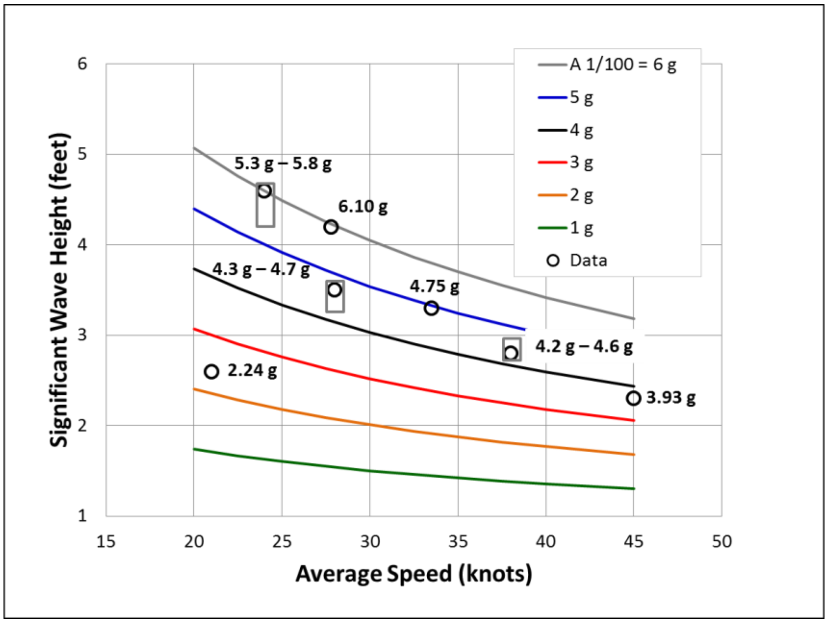

Figure 4. LCG $A_{1/100}$ Data Fit for 14,000 Lb. – 18,000 Lb. Craft

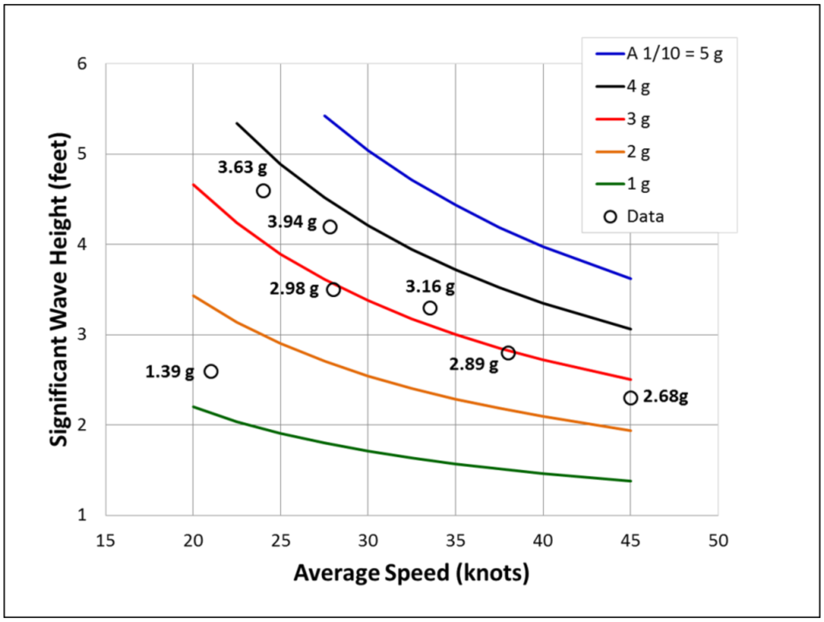

Figure 5. LCG $A_{1/10}$ Data Fit for 14,000 Lb. to 18,000 Lb. Craft

Equations for Category B Craft

The following trend equations apply to craft that weigh from 22,000 pounds to 38,000 pounds with lengths from 33 feet to 48.9 feet and beams from 9 feet to 15 feet. Eight of ten craft in Category B exhibited discernable $A_{1/100}$ trends during fourteen of sixteen runs. The fourteen runs included significant wave heights ranging from 2.4 feet to 5.7 feet and craft average speeds up to 39.6 knots. V_s is craft average speed in knots, and H is significant wave height in feet. A_{peak} is the peak amplitude for a single wave impact. These craft included deep-V planing, as well as one air entrapment hull and a catamaran. Values of $A_{1/100}$ are estimated within -0.25 g to +0.19 g (i.e., -10.50% to +10.72%) for 0.19 g < $A_{1/100}$ < 0.25 g, when H > 1.1 feet.

$$A_{1/100} = \frac{(V_S + 21)(H_{1/3} - 1.03) - 0.20}{56.83} \qquad \text{Equation (3)}$$

$$A_{1/10} = \frac{(V_S + 7.46)(H_{1/3} - 1.08)}{62.5} \qquad \text{Equation (4)}$$

The data base for $A_{1/10}$ values included two additional deep-V hull craft. Sixteen of eighteen runs fit the A1/10 trends within +12.4% to -11.1% of the data (i.e., +0.20g to -0.22 g). Figure 6 and Figure 7 show constant acceleration curves constructed using equations (3) and (4).

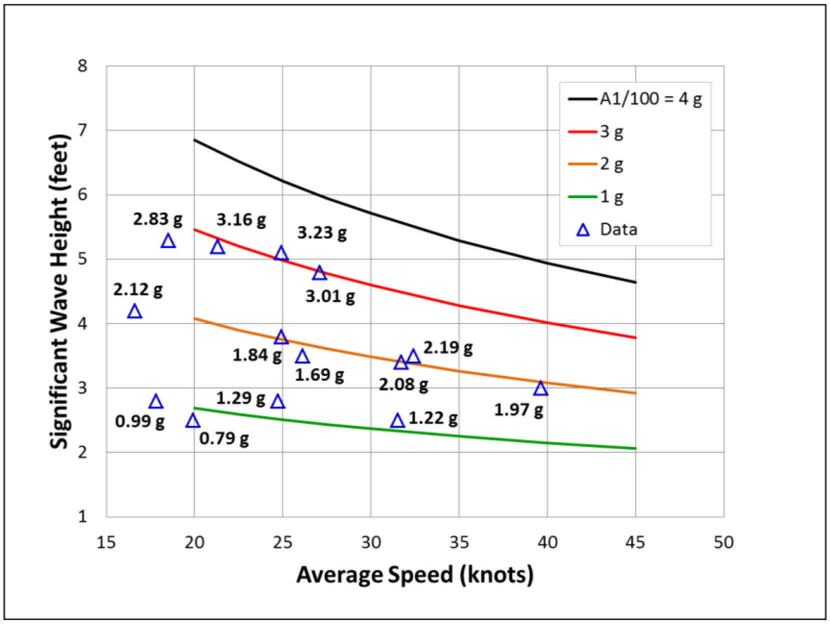

Figure 6. LCG $A_{1/100}$ Data Fit for 22,000 Lb. – 38,000 Lb. Craft

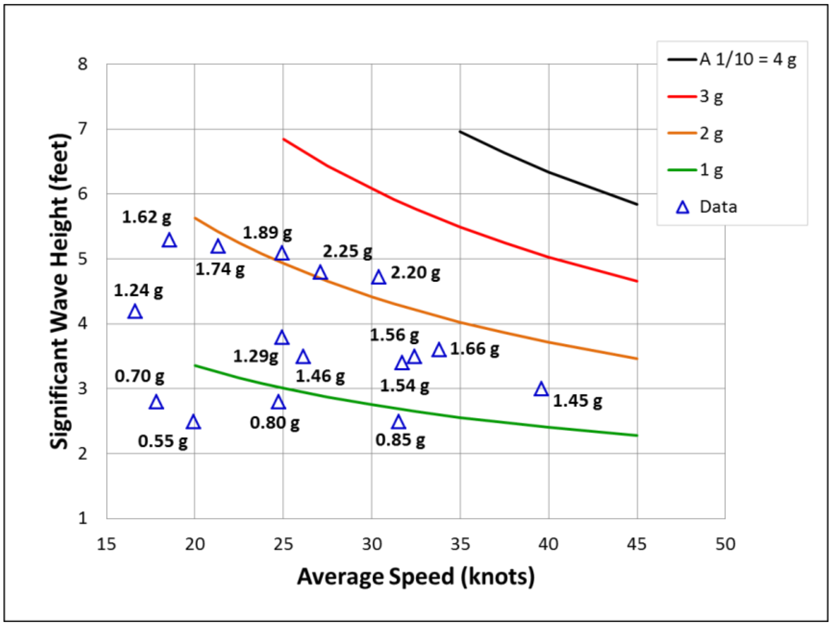

Figure 7. LCG $A_{1/10}$ Data Fit for 22,000 Lb. – 38,000 Lb. Craft

Based on a sensitivity analysis of the individual data points within the database, it was assumed that average craft speeds may vary during a trial on the order of +/- 3 knots, and that published significant wave heights from wave buoy data may vary on the order of +/- 6 inches depending upon the location of the buoy relative to the craft's actual position during seakeeping trials. The lines shown in the data plots should therefore be used to indicate transition zones rather than hard lines that yield exact numbers.

Crew Comfort and Performance Criteria

$A_{1/N}$ Acceleration Values

Ride quality criteria related to crew comfort and performance were originally published in terms of $A_{1/10}$ values. Values of $A_{1/10}$ equal to 1.0 g and 1.5 g at the LCG were developed as limiting values for crew tolerance based on feedback from naval crews just after high-speed trials in rough seas [7]. These levels where later used as hull design values to characterize "ride quality conditions" with exposure times that could be sustained with no loss of mission function [3]. It was reported that the severity of vertical accelerations in a planing craft characterized by $A_{1/10}$ less than 1.0 g corresponded to an environment where the crew could effectively perform their functions for 4 or more hours. A value of $A_{1/10}$ equal to 1.5 g corresponded to the crew being able to perform effectively for 1 to 2 hours exposure. The 1.0 g and 1.5 g $A_{1/10}$ criteria were subsequently published in papers along with other values listed in Table 2 [1, 7]. An $A_{1/10}$ value of 3.0 g was described as a level that would cause extreme discomfort. The $A_{1/10}$ = 4.0 g level

[7] DTNSRDC-SDD-114-24, August 1976

appears to be a transition to $A_{1/10}$ = 5.0 g which was associated with more severe effects. The injury level is beyond the scope of this report, but it is treated in other publications for high-speed craft applications [12 - 16].

Table 2. Acceleration Criteria for Personnel Effects

A 1/10 (g) at LCG	Effects on Personnel	A 1/100 (g)
1.0	Maximum for military function long term (over 4 hours)	1.54
1.5	Maximum for military function short term (1 - 2 hours)	2.31
2.0	Tests discontinued	3.08
3.0	Extreme discomfort	4.62
4.0		6.16
5.0	Physical injury	7.7
6.0	Military crew under fire	9.24

Analyses of data for both Categories A and B subsets observed that the $A_{1/100}$ values for all the trials were from 1.52 to 1.56 times the $A_{1/10}$ values. The ratio of $A_{1/100}$ to $A_{1/10}$ was on average equal to 1.54. This linear relationship means that both $A_{1/100}$ and $A_{1/10}$ values can be used to quantify how severe wave impacts were during a period of time. One is merely an average of the top ten percent of impacts, and the other is the average of the top one percent of impacts. As shown in Table 2, the $A_{1/10}$ ride quality criteria can also be tabulated in terms of the $A_{1/100}$ parameter for this subset of craft. The values of $A_{1/100}$ listed in the table were computed by multiplying the $A_{1/10}$ criteria by 1.54 to yield the same criteria in terms of $A_{1/100}$. For example, when speeds and sea states result in extreme discomfort, it can be quantified by an $A_{1/10}$ value of 3.0 g or an $A_{1/100}$ value of 4.62 g (for short wave periods for this subset of craft). Other craft with different hull form characteristics may exhibit different ratios between $A_{1/100}$ and $A_{1/10}$ (e.g., 1.6 to 2.0), so the values listed in Table 2 may not be appropriate for other subsets of craft.

The example plots presented below use the $A_{1/10}$ ride quality values to maintain continuity with the historical references.

Crew Comfort and Performance Transition Zones

The values listed in Table 2 are useful interim criteria for defining notional zones of operation where typical changes in human comfort and performance may occur. The values of 1.0 g and 3.0 g are selected as start and end conditions for defining the four severity levels shown in Table 3. The approximate $A_{1/10}$ value below which human comfort is sufficient to allow 4 or more hours of effective performance while underway is 1.0 g, and 3.0 g is the approximate $A_{1/10}$ value above which discomfort from wave impacts is judged to be extremely uncomfortable. Ranges between these values were developed to describe transition zones from general levels of comfort and performance to levels of discomfort and shorter performance periods. The 4.0 g limit for Level IV is included because it was cited as a severity transitioning from extreme discomfort to more severe effects [7]. Level III is intended to represent the transition between limited endurance (i.e., 1 to 2 hours) through a region of discomfort where endurance is less than

1 to 2 hours before reaching the extreme discomfort zone. The range of Level II is +/- 0.5 g on either side of the 1.5 g criterion to define a transition between limited and unlimited crew performance zones. In Table 3 the arbitrary shades of color are presented to illustrate how seakeeping data and acceleration severity levels (i.e., either $A_{1/10}$ or $A_{1/100}$ values) can be conveyed in a useful data plotting format for guidance documents.

Table 3. Recommended Crew Comfort and Performance Transition Zones

Severity Transition Zones	A 1/10	A 1/10 Range	A 1/100 Range	Condition
IV	3 g	3 g – 4 g	4.6 g - 6.1 g	Extreme Discomfort
III	na	2 g - 3 g	3.1 g - 4.6 g	Discomfort and limited mission performance
II	1.5 g	1 g - 2 g	1.5 g - 3.1 g	Effective mission performance for 1 - 2 hours
I	1 g	<1 g	< 1.5 g	Effective mission performance for 4 or more hours

Experienced test personnel explain that several factors can affect a helmsman’s decision regarding a safe speed for prevailing wave heights, including concern for stuffing the bow when wave heights are large, concern for safety of self and passengers to avoid extreme discomfort or injury, or concern because items are starting to break on the craft. Maximum speed can also be achieved during rough-water sea trials when the craft has reached its power limit. This is especially true in lower significant wave heights in the 2-foot to 3-foot range where the craft’s maximum speed can be achieved before safety becomes a concern. In the current data base, two trials were performed with significant wave heights of 2.1 feet and 2.6 feet at speeds approaching the maximum rated speeds.

Craft Speed versus Wave Height Envelopes

Craft Category A Example Envelopes

Figure 8 shows example ride severity envelopes computed using equation (2) and the transition zones listed in Table 3 for craft that weigh from 14,000 pounds to 18,000 pounds.

Craft Category B Example Envelopes

Figure 9 shows example ride severity envelopes computed using equation (4) and the transition zones listed in Table 3 for craft that weigh from 22,000 pounds to 38,000 pounds.

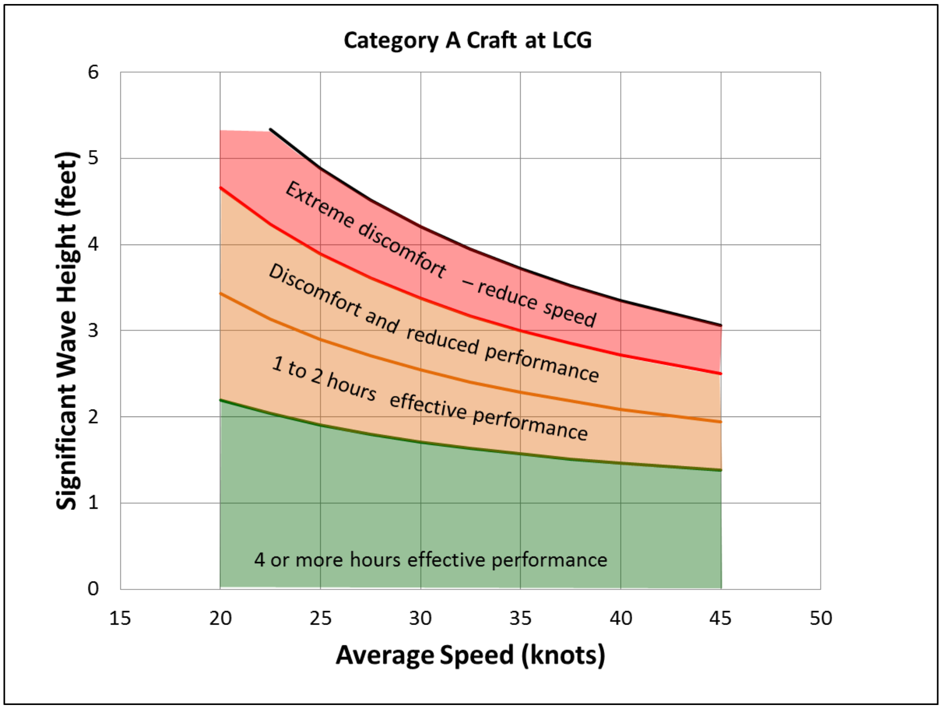

Figure 8. Ride Severity Envelopes for 14,000 Lb. – 18,000 Lb. Craft

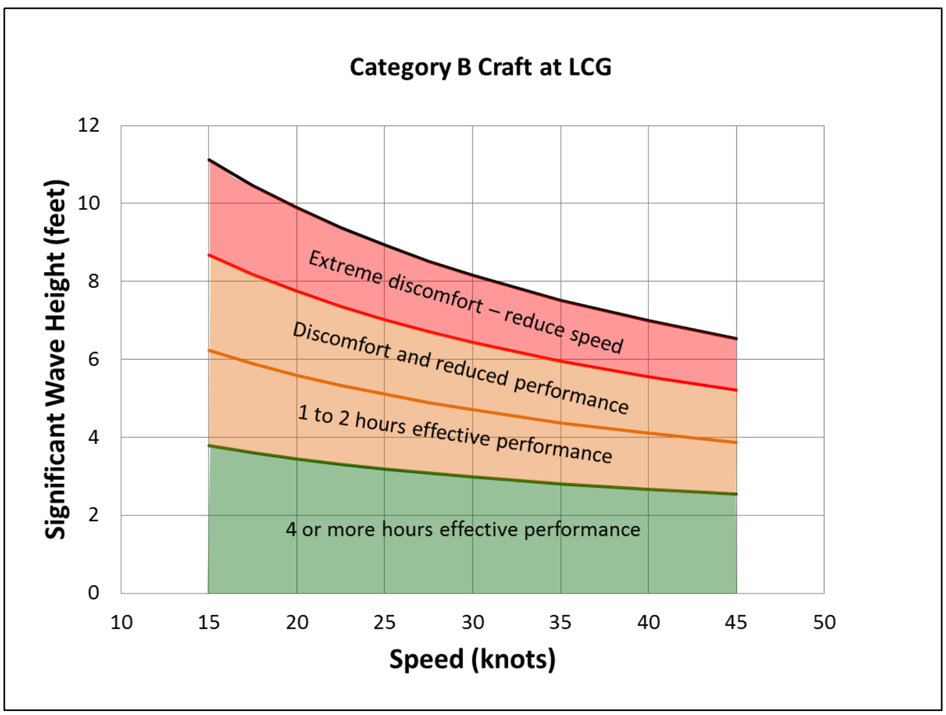

Figure 9. Ride Severity Envelopes for 22,000 Lb. – 38,000 Lb. Craft

Observations

Comfort and Performance Criteria

The ride quality criteria listed in Table 2 should not be interpreted as fixed values that apply equally to all individuals, nor are they exact acceleration numbers that correspond precisely with specific comfort levels. People can exhibit large variations in their perceptions of the environment, and the tolerance of one person may not be consistent [9, 10]. For example, hypothetically, one individual may experience 1 to 2 hour limited performance after being exposed to $A_{1/10}$ equal to 1.5 g while another individual may experience the same effects at 1.8 g. They are historical criteria that should be considered interim values until further trials can be performed to systematically investigate parameters and conditions that affect human performance and comfort in a wave impact environment.

Extrapolation of Limited Data

The existing data for high-speed planing craft are limited to specific ranges of speed, significant wave height, and LCG acceleration values. For example, for the lighter Class A craft (see Figure 5), there is only one data point less than $A_{1/10}$ equal to 2 g at the LCG and only two data points greater than 3.5 g. For the heavier Class B craft (see Figure 7), there are only two data points greater than $A_{1/10}$ equal to 2.0 g at the LCG. Until further data is available, envelope predictions of LCG $A_{1/10}$ values beyond these ranges are extrapolations outside the existing data base that should be confirmed by future data.

Craft Heading and Wave Length

Wave height versus speed envelopes should be constructed for the most severe combination of craft heading and wave length [2].

Craft Heading

During full-scale seakeeping trials at constant speeds the head sea direction almost always results in larger wave impact vertical accelerations compared to other directions (i.e., the most unfavorable condition). Figure 10 shows example deck data consisting of RMS, A_{avg}, $A_{1/3}$, $A_{1/10}$, and $A_{1/100}$ accelerations for head seas compared to values for other directions, including bow-quartering, beam, stern-quartering, and following seas. The format of the plot that compares peak acceleration statistics for different conditions is referred to as a ride severity index plot [17]. In this format data points that fall on the dotted line with a slope of 1:1 are equal. The craft average speed was 30.4 knots for all runs and the significant wave height was approximately 4.6 feet. The bow-quartering data is similar to the head-sea data with values on the order of 5 percent less than head-sea data (i.e., average slope of 0.95). Beam-sea data is roughly half the head-sea data (slope 0.55), data for following seas is roughly one-third of head-sea data (slope 0.32), and stern-quartering data is roughly one-fourth of head-sea data (slope 0.23). These ratios typically vary for different craft as sea state and speed varies. Wave height versus speed envelopes could be constructed for all of the directions, but empirical equations have only been developed for the most severe head-sea direction. It is recommended that head-sea acceleration data be used to construct wave height versus speed envelopes, unless otherwise indicated by seakeeping data. For example, depending upon wave length conditions relative to the length of the craft, the bow quartering peak accelerations may be larger than head sea vertical peak accelerations.

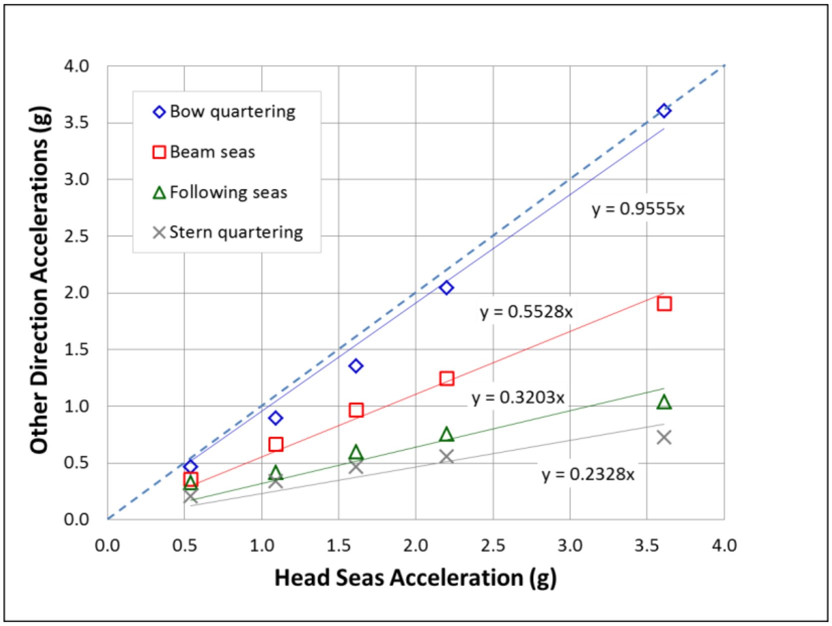

Figure 10. Example Head Sea Accelerations versus Other Directions

Wave Length and Wave Period

Depending upon average speed and wave height, smaller planing craft within the scope of this report tend to follow the wave profile with less bow-up and bow-down pitching when wave lengths are relatively long. In this environment, the craft seldom becomes airborne and experiences more wave encounters with little or no pitching. Vertical peak accelerations are typically on the order of 2.0 g to 2.5 g or less at the LCG under these conditions. When wave lengths are shorter, small craft may become airborne or partially airborne when average speeds and wave heights increase. This behavior has been observed in full-scale Category A craft (volumetric Froude number 2.1 to 3.1) and in scale-model data [18] (volumetric Froude number greater than 4.5). Even if they do not become airborne, they can experience large bow-up pitching motions especially in higher sea states and at higher speeds. This is especially true for the lightest weight Category A craft (i.e., 14,000 pounds to 18,000 pounds). Large pitching motions or becoming airborne (i.e., even partially) can lead to vertical peak accelerations on the order of 3.0 g to 7.0 g (i.e., rigid body heave acceleration) or higher depending upon craft weight, wave height, trim, deadrise, and speed. The shorter wave period environment is therefore the more severe environment for developing wave height versus speed envelopes.

The majority of the full-scale database used in the study was acquired during trials conducted off the east coast of the United States. East coast waves usually, but not always, have shorter wave periods (e.g., 6.5 seconds or less) and smaller wave lengths for a given wave height than west coast waves, or seas further off-shore in open ocean.

Figure 11 compares seakeeping data for peak accelerations in an 8-second wave period on the west coast of the U.S. compared to peak accelerations recorded on a similar craft in a 5-second wave period on the east coast of the United States. The similar craft were 44 feet long

and weighed approximately 37,000 pounds. The west coast wave length was on the order of 212 feet while the east coast wave length was about 90 feet. The trials had comparable wave heights (3.1 feet versus 3.4 feet) and comparable average speeds (38.3 knots versus 34.8 knots, respectively). The comparison shows the longer wave period (i.e., longer wave length) resulted in vertical accelerations on the order of 42-percent less than the vertical accelerations for the shorter wave period (i.e., shorter wave length).

Unless the small planing craft's operating area will always be in the longer wave length environment (e.g., like the west coast of the U.S.), it is recommended that acceleration data for the short wave length data be used to develop wave height versus speed envelopes. Equations (1) thru (4) were developed using short wave length east coast data.

Ride severity envelope estimates for west coast operations could be estimated by substituting scaled accelerations from Figure 11 into equations (3) and (4).

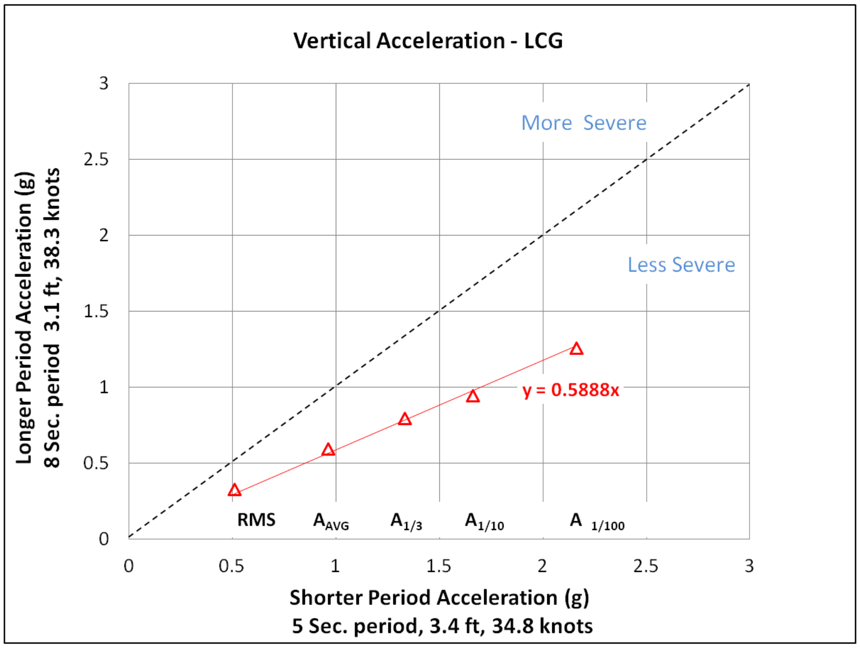

Figure 11. Effect of Wave Period on Impact Accelerations

Conclusions and Recommendations

The empirical equations presented in this report are based on limited seakeeping data. In the absence of craft specific data, they may be used to estimate wave height versus speed envelopes for high-speed planing craft that fall within the weight ranges and characteristics of Category A and Category B craft. The equations are based on observed trends in data recorded during seakeeping trials when craft were operating in head seas with relatively short wave lengths (i.e., east coast short wave period of 6.5 seconds or less). These conditions are the most unfavorable combination of parameters that typically leads to larger wave impact accelerations compared to longer wave length conditions (i.e., west coast longer wave period) or beam, quartering, or following seas. Envelope predictions for speeds and wave heights outside the range of speeds and wave heights achieved during the trials are extrapolations that should be confirmed by future data.

Acceleration values corresponding to different levels of crew mission performance degradation and crew comfort were originally developed based on seakeeping trials data. In the absence of more recent full-scale data, it is recommended that the acceleration values listed in Table 2, either $A_{1/10}$ or $A_{1/100}$ values, be used as interim criteria for constructing ride severity envelopes. These single number criteria can be transitioned to ranges of values that are listed in Table 3.

It is recommended that additional seakeeping trials be conducted to systematically investigate parameters and conditions that affect human performance and crew comfort in a wave impact environment. In addition to vertical acceleration values, other parameters like fore-aft acceleration, pitch rate, and roll rate should be included in the study. The trials should include head-sea runs at three different planing speeds (e.g., with greater than 6 knot separation if possible) in three different significant wave height conditions (e.g., with greater than 1 foot separation if possible) with average wave periods less than approximately 6.5 seconds.

Symbols, Abbreviations, and Acronyms

A .... Vertical peak-acceleration
A_{AVG} .... Average vertical acceleration
$A_{1/10}$ .... Average of the 1/10th highest peak accelerations
$A_{1/100}$ .... Average of the 1/100th highest peak accelerations
$A_{1/N}$ .... Average of the 1/Nth highest peak accelerations
A_{peak} or A_{max} .... Maximum or peak wave impact acceleration pulse
B .... Craft beam
CCD .... Combatant Craft Division
ft .... Feet
g .... 32.2 ft/sec^2 acceleration due to gravity
$H_{1/3}$ or H .... Significant wave height
Hz .... Hertz
K .... Kilo
L .... Craft overall length
LCG .... Longitudinal center of gravity
lb. .... Pound
N .... Number of wave impacts
NSWCCD .... Naval Surface Warfare Center Carderock Division
rms .... Root mean square
V .... Craft average speed

References

1. Koelbel, Joseph G., Jr., “Seakeeping and Seakindliness – The Effect of Hull Form, Center-of-Gravity, and Other Factors on the Comfort of Those Aboard in a Seaway”, Symposium on the Design and Construction of Recreational Power Boats, University of Michigan, Department of Naval Architecture and Marine Engineering, Ann Arbor, Michigan, August 20 – 24, 1979.

2. “Guide for Building and Classing High-Speed Craft”, American Bureau of Shipping, Publication 61, Part 1, Rules for Condition of Classification, March 2013.

3. Hubble, E.N., “Performance Predictions for Planing Craft in a Seaway”, David Taylor Naval Ship Research and Development Center Report DTNSRDC-SPD-0840-02, September 1980.

4. Blount, Donald L., Hankley, Donald W., “Full-Scale Trials and Analysis of High-Performance Planing Craft Data”, The Society of Naval Architects and Marine Engineers Annual Meeting, November 11-13, 1976, New York, NY.

5. Coats, T., Haupt, K., Jacobson, D., Jacobson, A., Pogorzelski, D., “MAST 2007 Working Towards Vertical Acceleration Data Standards”, Naval Surface Warfare Center Report NSWCCD-TM-23-2007/16, September 2007.

6. Koelbel, J.G., Jr., “Comments on the Structural Design of High Speed Craft”, Marine Technology, Volume 32, No. 2, April 1995, pp. 77-100.

7. Savitsky, Daniel, Koelbel, Joseph, “Seakeeping of Hard Chine Planing Hulls”, SNAME, Technical and Research Bulletin No. R-42, June 1993

8. Riley, M., Haupt, K., Jacobson, D., “A Generalized Approach and Interim Criteria for Calculating $A_{1/n}$ Accelerations Using Full-Scale High-Speed Craft Data”, Naval Surface Warfare Center Report NSWCCD-TM-23-2010/13, April 2010.

9. Payne, Peter R., “On Quantizing Ride Comfort and Allowable Acceleration”, AIAA/SNAME Advanced Marine Vehicle Conference, paper 76-873, Arlington, VA., September 20-22, 1976.

10. “Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole-Body Vibration, Part 1, General Requirements”, International Organization for Standardization, ISO 2631-1:1997(E), July 1997.

11. Zseleczky, John, “Behind the Scenes of Peak Acceleration Measurements”, The Third Chesapeake Powerboat Symposium, Annapolis, Maryland, USA, 14-15 June 2012.

12. “Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole-Body Vibration”, ISO-2631-5:2004(E), International Organization for Standardization, Geneva, Switzerland, 2004.

13. Bass, C., Salzar, R., Ziemba, A., Lucas, S., Peterson, R., Price, E., “Dynamics Models for the Assessment of Spinal Injury from Repeated Impact in High Speed Planing Boats”, Proceedings of the International Research Council on the Biodynamics of Injury (IRCOBI): 397-400, Maastricht, The Netherlands, 19-21 September 2007.
14. Pierce, E., Price, B., Blankenship, J., LaBrecque, J., Bass, D., “Industry Day Briefing, Impact Injury Assessment for Combatant Craft Medium (CCM), unpublished presentation, 10 December 2008.
15. Schmidt, A.L., Paskoff, G., Shender, B.S., Bass, C.R., “Risk of Lumbar Spine Injury from Cyclic Compressive Loading”, Spine Magazine, Volume 37, Issue 26:E1614-E1621, 15 December 2012.
16. Department of Defense Design Criteria Standard, “Human Engineering”, Military Standard, MIL-STD-1472G, paragraph 5.5.5, 11 January 2012.
17. Riley, Michael R., Coats, Dr. Timothy W., Haupt, Kelly D., “Ride Severity Index: A Simplified Approach to Comparing Peak Acceleration Responses of High-Speed Craft”, The Society of Naval Architects and Marine Engineers, Journal of Ship Production and Design, Vol. 29, No. 1, February 2013, pp. 1 – 11.
18. Blount, Donald L., Funkhouser, Jack, “Planing in Extreme Conditions”, High performance marine Vehicles, American Society of Naval Engineers High Performance Marine Vehicle Symposium, Linthicum, MD, 9-10 November 2009.
19. Riley, Michael, R., Coats, Timothy, W., “Acceleration Response Mode Decomposition for Quantifying Wave Impact Load in High-Speed Planing Craft”, Naval Surface Warfare Center Report NSWCCD-TR-80-2014/007, April 2014.

Distribution

	Copies
J. M. Coughlin	1
C. Rozicer Naval Sea Systems Command PMS 325G 1333 Isaac Hull Avenue S.E. Washington Navy Yard D.C. 20376-1070	1
J. Zseleczky U. S. Naval Academy Hydromechanics Laboratory 590 Holloway Road Annapolis, MD 21402	1
Commander Naval Special Warfare Dev Group 1639 Regulus Avenue Virginia Beach, VA 23461-2299 Attn: Mr. Joseph Coles, Code N54-4	1
David Shepard United States Coast Guard Office of Boat Forces, CG 731 2100 Second Street, SW STOP 7356 Washington, DC 20593-7356	1

NSWC, CARDEROCK DIVISION
INTERNAL DISTRIBUTION

Code	Name	Copies
83	Electronic Data Library	1
85	Dr. A. Becnel	1
87	Dr. J. Gorski	1
801	Dr. T. Fu	1
83R	Dr. T. Coats	1
831	W. Sokol	1
831	J. Marshall	1
833	K. Beachy	1
835	D. Pogorzelski	1
835	K. Haupt	1
835	H. Murphy	1
835	C. Weil	1

NSWC, PANAMA CITY

Code	Name	Copies
E41	Eric Pierce	1
E23	Brian Price	1
E41	Jeff Blankenship	1

Appendix A. Rigid Body Acceleration

The steps required to properly analyze acceleration data begins with the fundamental concept of input and response. The load of a single wave impact (i.e., the input to the craft) causes a deterministic response. The word deterministic is used here because the response at a location on a craft is neither random, nor is it chaotic. For a specific set of load conditions, like pulse amplitude, duration, pressure distribution, deadrise, trim, speed, and wave height, there is a unique and repeatable response (as long as permanent deformation of the structure does not occur). Figure A1 illustrates the input and response concept with a mathematical single-degree-of-freedom model oriented in the vertical direction. It is single-degree because the only mode of response motion is up-and-down displacement. There is no rotation of the mass in the model nor is there side-to-side motion. The letter *m* represents the mass of the system of interest, the letter *k* represents the stiffness of the deck and stiffeners between the mass and the point of load application, and the letter *c* represents the damping characteristics of the deck and stiffeners between the mass and the point of load application. The letter *t* signifies that the load and the response vary over time.

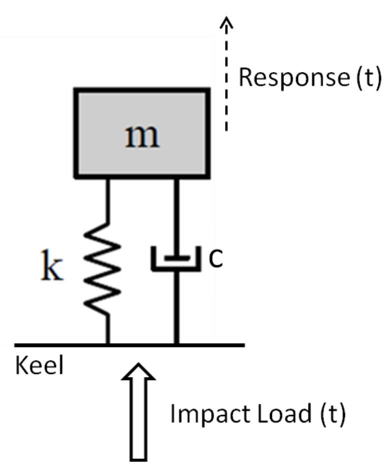

Figure A1. Single-Degree-of-Freedom Input and Response Model

The concept of rigid body motion is a mathematical construct used to model forces, (including impulsive loads), momentum transfers (or energy transfers), and the dynamic response of systems. The mathematical equations of motion that describe the dynamic response of the mass (*m*) in Figure A1 can be written in terms of the applied force (i.e., in this case the impact load) or in terms of the vertical motion of the base at the point of load application. The vertical motion at the base can be described in terms of either time histories of displacement, velocity, or acceleration, whichever is more convenient.

Unfortunately, during seakeeping trials, there are no practical force gages with which to directly measure the force of each wave impact. As a mathematical substitute, the absolute motion of the base can be used as an input to the mathematical model. Since accelerometers are typically used, the base input is conveniently described in terms of the heave acceleration. The heave acceleration is the vertical rigid body acceleration of the craft. The vertical rigid body acceleration at a cross-section of a craft can therefore be used as a measure of the net vertical force (i.e., the load) acting at that cross-section. It is a measure of wave impact load severity.

But real systems also experience internal relative motions caused by flexure of structural elements. Accelerometers are very sensitive instruments that measure flexural motions of deck plates and stiffeners and rigid body motions like heave, surge, pitch, and roll. The recorded acceleration is therefore a superposition of different response modes that depend upon the location of the gage [19].

In order to extract the rigid body acceleration from the record, the recorded acceleration must be decomposed into its different modes of response. This process is referred to as modal decomposition.

Analyses of a Fourier spectrum of an unfiltered acceleration time history can be used to decompose the unfiltered record in the frequency domain into its different modes of response. The modes of response include rigid body modes, local deck and stiffener flexural modes (i.e., local response vibrations), response modes of isolated equipment or shock mitigation seats, and, if the craft is large enough, global hull-girder flexure.

In the absence of a practical hull force gage or pressure gage, the impulsive load of a wave impact can be quantified in units of *g* by the amplitude and duration of the rigid body acceleration response during the impact. The rigid body acceleration response can be decomposed from an unfiltered acceleration record by using a low-pass filter. For small high-speed planing craft less than 100 feet in length it is recommended that a 10-Hz low-pass filter be used, unless Fourier spectrum analysis indicates some other value [8]. If a different value is used, it should be published with the analysis results.

In the time domain the concept of modal decomposition is illustrated by the three plots on the left shown in Figure A2. Each plot is a 10-second segment of acceleration data that shows six wave impacts. The accelerometer was oriented vertically and installed on the deck above a support stiffener at the LCG. The red curve in the upper plot is the unfiltered vertical acceleration. The middle plot is the vertical rigid body acceleration extracted from the unfiltered acceleration by low pass filtering. It shows three severe wave impacts where the wave slam spikes are clearly visible. The rigid body acceleration is also shown as the black curve in the upper plot to show how the vibration content rides on the rigid body acceleration. The bottom plot is the deck vibration content obtained by high-pass filtering. When the rigid body and the vibration responses are added it creates the original unfiltered curve shown in the upper plot.

In the frequency domain the rigid body content and the vibration content are observed as spikes and humps in the Fourier spectra shown on the right side of Figure A2. They are Fourier spectra of the three plots shown on the left side. The upper plot is the Fourier spectrum of the unfiltered acceleration record. It shows the rigid body content at frequencies less than 4 Hz and several dominant vibration modes in the vicinity of 25 Hz and 43 Hz. The spectrum of the rigid body content and the spectrum of the vibration content are shown to illustrate the modal decomposition process and how low-pass and high-pass filtering are used to decompose the unfiltered signal.

An unfiltered acceleration record should initially be labeled in units of length per time-squared because it is a recording of the rate of change of velocity at the location of the gage. If data plots of unfiltered acceleration time histories are normalized by dividing by the acceleration due to gravity they should not be labeled *g-load*.

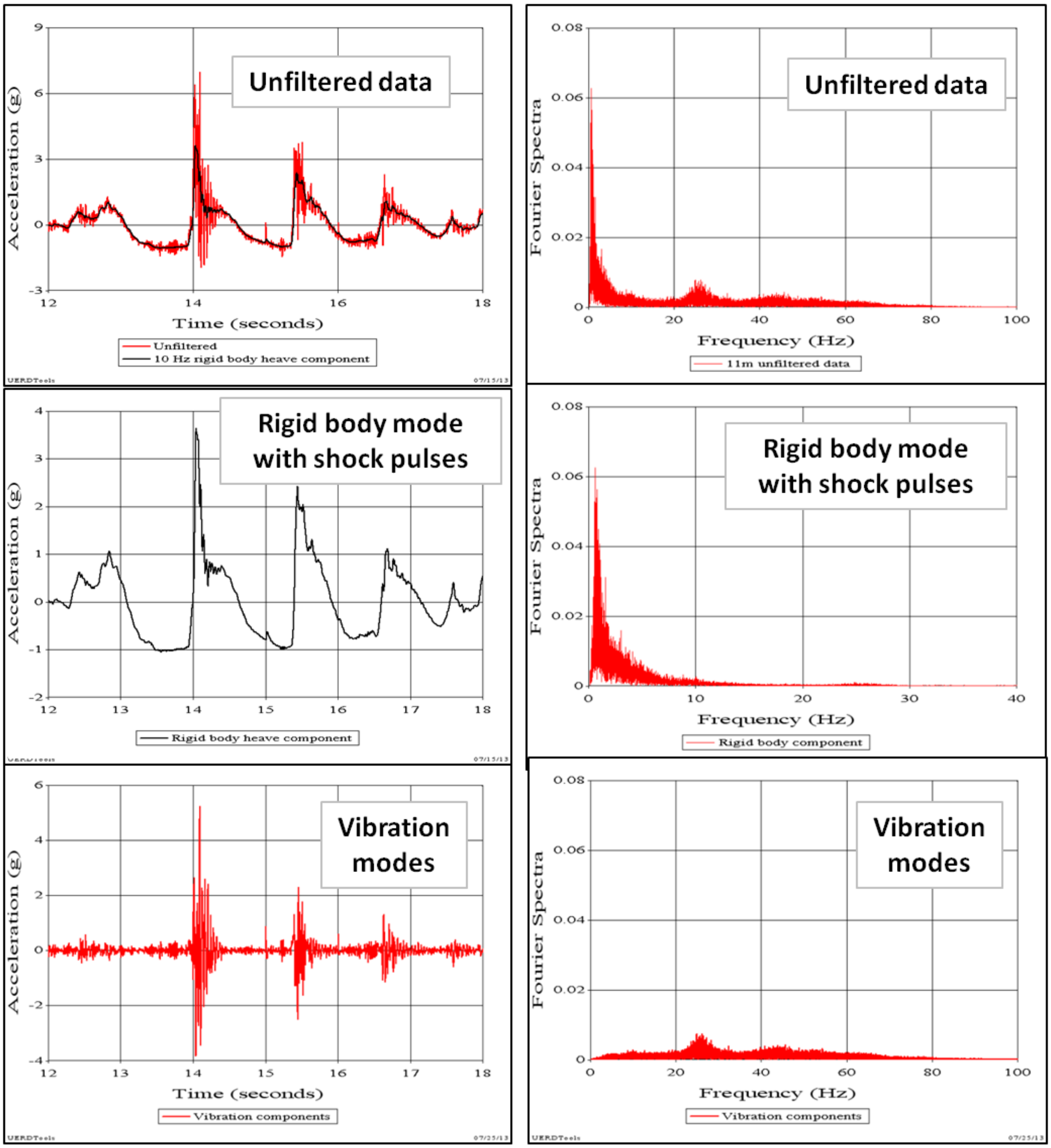

Figure A2. Modal Decomposition of Stiff-Deck Acceleration Data

NAVSEA
WARFARE CENTERS
Carderock